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Review

Investigation of combustion and co-combustion characteristics of raw and thermal treated bamboo with thermal gravimetric analysis

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ABSTRACT

The thermal behaviour and chemical characteristics of the bamboo species, *Bambusa multiplex* (BM), sourced from South Africa were investigated using thermogravimetric analysis (TGA). Torrefaction and low-temperature carbonization conditions were applied to samples of this plant at temperatures between 250 °C and 380 °C. The burning profiles for the raw and thermally treated bamboo samples co-fired with coal A at different ratios of coal inclusion were examined. The raw BM was found as the easiest to ignite fuel probably due to possessing the highest volatile matter content.

Considerable differences in fuel characteristic were found between the raw and thermally treated BM samples. Raw BM was found to have a calorific value of 17.60 MJ/kg, whereas, torrefied and low temperature carbonized BM produced fuels of 23 MJ/kg and 28 MJ/kg, respectively. Further results attained in this investigation on basis of combustibility, has shown the relatively low ignition temperatures and highly reactive potential of torrefied bamboo samples.

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Contents

1. Introduction 207
2. Experimental 208
    2.1. Materials and thermal treatment 208
    2.2. Differential thermogravimetric (DTG) test on biomass and co-fired coal 209
    2.3. Material characteristics, energy and mass yield 210
3. Result and discussion 210
    3.1. Physico-chemical properties of the coal and bamboo samples 210
    3.2. Energy characteristics of the coal and bamboo samples 210
    3.3. The effect of thermal treatment on bamboo characteristics 210
    3.4. Combustion profile of coal A, raw and thermal treated Bambusa multiplex samples 211
    3.5. DTG profile for blends of raw BM and Coal A at different weight ratio 211
    3.6. DTG profile for blends of TBM (250 °C and 280 °C) and Coal A at different wt% ratios 212
    3.7. Effect of low-carbonization temperatures (350 °C and 380 °C) and coal blending on co-combustion characteristic of bamboo and coal 213
4. Conclusions 213
    Acknowledgements 214
    References 214

1. Introduction

Biomass is defined as a biological and sustainable material originated from plants in a woody and non-woody form, respectively. Bamboo is known as a woody biomass, which has shown positive prospect as a future energy source due to its fast growth rate, strength and high quality fuel physiochemical properties such as

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low ash content, high calorific value, and low alkalis index [1]. The increasing investigation on biomass such as bamboo for power generation solely, or co-fired with coal, is as a result of increase in the global outcry to reduce fossil fuel dependence. With many techniques available for converting biomass or co-firing it with coal to generate energy, biomass still faces different shortcomings, such as different physiochemical properties, varied combustion characteristics, difference in energy density when blended with coal, high grindability and handling cost, low energy yield and high moisture and volatile components [2–4].

Thermal pre-treatment of biomass is a process used to increase the energy yield of biomass, eliminate biodegradation, and improve grinding and handling properties along with homogenization for combustion and co-firing with coal. The application of this technique was found by Park and Jang [4] to have a major influence on the chemical and physical properties of raw biomass. Investigation on the thermal pre-treatment and decomposition of the *Bambusa multiplex* (BM) utilized in this research will provide a better understanding of its combustion reactivity as a co-fired fuel or a solely fired fuel. However, low burning rate and low flame temperatures of biomass, which results in poor flowability, poor blending and a reduction in thermal efficiency and capacity of existing boiler units are additional challenges facing biomass as co-fired fuel [5,6]. Nevertheless, it is proposed that some of the aforementioned limitations should be addressed through the thermal treatment of the raw bamboo leading to the production of a biomass with high valuable and renewable energy source.

The impact of different pre-treatment methods such as torrefaction, carbonization and pelletisation in achieving high quality biomass that could be co-fired with coal to attain high quality co-firing combustion characteristic, low CO_2 and NO_2 emissions have been investigated by many researchers [3,7,8]. Torrefaction is known to facilitate the homogenization of biomass through the decomposition of hemicellulose, which is the most reactive component of the polysaccharides or lignocellulosic constituents of biomass. With the torrefaction of biomass, an investigation conducted by Brzdekiewicz et al. [9] on the effect of biomass substitution at different weight blends in a coal firing boiler on temperature and gas components has shown similar flue gas temperature distributions for all composition of fuels tested. The same authors also found a significant reduction in the NOx emissions for torrefied biomass relative to coal as a result of the lower nitrogen content of biomass, and more so, due to the conversion of nitrogen in biomass volatiles to NH_3 [10].

Phanphanich and Mani [3] reported a ten-fold reduction in energy required for grinding pine chips torrefied at 300 °C and a six-fold reduction for torrefied logging residues compared to untreated biomass. The authors also showed that the energy required in grinding woody biomass torrefied between 275 and 300 °C could be improved by 23–78 kWh/t, similar to energy used in grinding coal (i.e. 7–36 kWh/t). A reduction of about 85% in power utilized in grinding torrefied willow was also reported by Svoboda [11]. Studies have also shown that the energy and mass yield from the low carbonization of biomass is different to that obtained during torrefaction. The investigation conducted by Park et al. [12] on different biomasses supported the fact that pyrolysis at low temperature between 400 and 500 °C improved fuel characteristics such as increased calorific value, higher fixed carbon and lower volatile matter. This increased the product's characteristics towards that of coal on the H/C vs. O/C diagram. This significant improvement in fuel characteristics was reported to be as a result of the decomposition of cellulose and hemicelluloses constituents in the biomass at this low carbonization temperature.

The species of bamboo utilized in this investigation (*Bambusa multiplex*) i.e. BM, was acquired from the Western Cape region of South Africa. *Bambusa multiplex* has a slender culm, a height within the range of 7–15 m, an internode of about 15–30 cm and it is utilized for construction and crop supports. Two other potential bamboo species planted in South Africa have also been identified for future combustion and co-combustion tests based on the data obtained from the preliminary investigation conducted on these two species, as depicted in Fig. 1. However, to date there has been very little conducted on the potential of bamboo grown in Southern Africa for power generation. For this reason, this research set out to test the torrefaction and low carbonization thermal treatment process on BM, and thereafter to investigate the effectiveness of different torrefaction and carbonization temperatures on the fuel basic characteristics including calorific value, carbon content, nitrogen and volatile matter content. In addition, the combustion profiles of both torrefied and carbonized biomass, along with biomass/coal blends at different ratios using differential thermogravimetric (DTG) techniques were evaluated.

2. Experimental

2.1. Materials and thermal treatment

Bambusa multiplex bamboo samples (referred to as raw BM) and coal were utilized as the raw biomass material and co-fired fuel in this investigation respectively. The bamboo culms were divided into different sections representing the leaves, top, middle and bottom of the stem and the root as shown in Table 1. The samples were

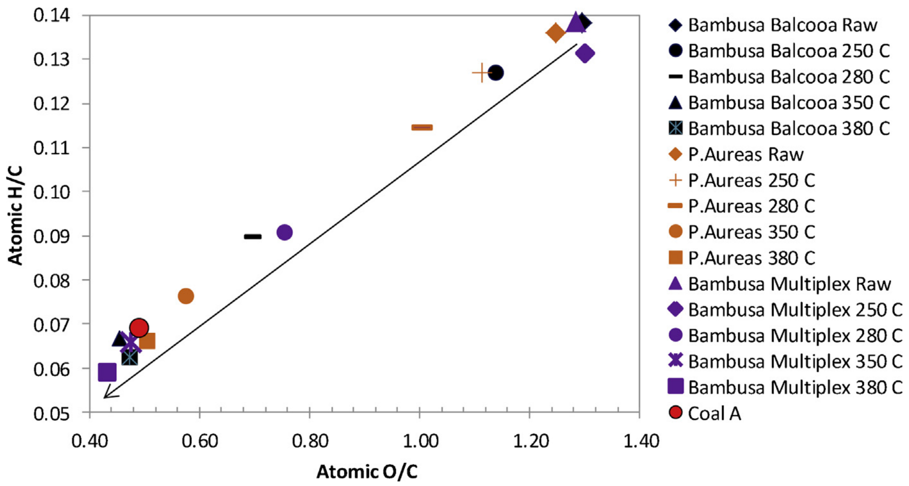

Fig. 1. Van Krevelen plot on coal, raw and thermal treated bamboo species.

Table 1
Proximate analysis of raw, torrefied and carbonized *Bambusa mutiplex* culms.

	M (%)	FC (%)	VM (%)	Ash (%)	Ash dry (%)	FC dry (%)	VM dry (%)
Raw BM							
Leaves	7.47	4.14	79.82	8.56	9.25	4.47	86.28
Top	7.08	2.12	89.02	1.77	1.91	2.28	95.81
Middle	5.83	3.45	89.96	0.76	0.81	3.67	95.52
Bottom	13.53	1.27	83.00	2.20	2.54	1.47	95.99
Root	13.39	1.05	84.43	1.13	1.30	1.21	97.49
Total blend	9.49	1.55	87.98	0.99	1.09	1.71	97.2
TBM @ 250							
Leaves	4.13	7.17	80.03	8.66	9.03	7.47	83.50
Top	3.98	9.88	85.89	0.26	0.27	10.29	89.44
Middle	4.83	8.94	86.06	0.17	0.18	9.40	90.42
Bottom	5.03	6.39	88.53	0.05	0.05	6.73	93.22
Root	5.01	10.07	79.67	5.24	5.52	11.26	83.22
Total blend	4.51	6.72	85.53	3.24	3.39	7.04	89.56
TBM @ 280							
Leaves	4.15	5.47	81.73	8.65	9.03	5.71	85.26
Top	5.95	27.14	60.42	6.48	6.90	28.86	64.24
Middle	3.75	15.09	79.58	1.58	1.64	15.70	82.66
Bottom	3.57	15.82	79.71	0.90	0.94	16.41	82.65
Root	2.98	24.10	66.51	6.41	6.60	24.84	68.56
Total blend	3.43	26.67	65.71	4.18	4.33	27.62	68.05
CBM @ 350							
Leaves	3.87	14.07	70.93	11.12	11.57	14.64	73.79
Top	5.33	38.40	52.53	3.74	3.95	40.56	55.49
Middle	3.62	46.21	47.87	2.29	2.38	47.95	49.67
Bottom	4.89	25.73	67.61	1.77	1.86	27.05	71.09
Root	3.26	37.90	54.69	4.15	4.29	39.20	56.51
Total blend	3.85	39.93	52.37	3.85	4.01	41.53	54.46
CBM @ 380							
Leaves	3.86	15.72	69.40	11.03	11.47	16.35	72.18
Top	3.98	45.10	47.98	2.93	3.05	47.00	49.95
Middle	3.99	50.36	43.88	1.76	1.83	52.45	45.72
Bottom	4.19	39.57	52.66	3.58	3.73	41.30	54.97
Root	4.01	40.38	47.51	8.11	8.45	42.07	48.85
Total blend	4.05	43.67	47.06	5.22	5.44	45.51	49.05

M: moisture; VM: volatile matter and FC: fixed carbon.

first subjected to a thermal treatment process known as torrefaction, which is a mild pyrolysis process conducted within the range of 200–300 °C under an inert environment. The aim was to produce a densified solid with improved grindability and more coal-like properties, which can be compared with low carbonized products. Torrefication of the raw BM bamboo was conducted at 250 °C and 280 °C based on the fact that torrefaction of biomass below 250 °C will produce products with poor grindability and above 300 °C will yield products with decomposed cellulose and lignin [13].

In addition, raw BM bamboo was also subjected to further thermal treatment "low-carbonization". This is a process which takes place under more intense and higher temperature compared to torrefaction, and in an oxygen free environment. The solid fuel produced from this process is carbon-rich, easy to grind, with higher energy density compared to raw and torrefied biomass. To further improve the fuel physico-chemical properties of the raw BM, low carbonization was conducted at 350 °C and 380 °C. The thermal treatment of the bamboo samples were conducted in a gas tight muffle furnace at a constant heating rate of 4 °C/min under argon and held for 1 h. The bamboo samples were air cooled, and milled using a Retsch PM 100 cutting mill to −212 μm size fraction. Several blends of coal and bamboo were then prepared from raw BM, torrefied BM (TBM 250 °C and TBM 280 °C) and low-carbonized BM (CBM 350 °C and CBM 380 °C) and adding at 10%, 30%, 50% and 75% of coal A by weight for the investigation. Coal A is used predominately in the blending tests, while coal B is included only by the way of comparison as seen in Fig. 1. In addition, the fuel characteristics of the two other bamboo species identified as a potential carbon rich and combustion fuel were plotted on the Van Krevelen graph after conducting a preliminary thermal test on these two different species.

2.2. *Differential thermogravimetric (DTG) test on biomass and co-fired coal*

The thermogravimetric analysis (TG) was conducted in a TGA 701 Leco, under an inert atmosphere with 50 mg of fuel used for each experiment. The operating procedure involved heating all samples at a constant heating rate of 25 °C/min, from 25 °C to 900 °C under air held until there is constancy in weight loss. These step parameters and conditions were applied to coal A, raw BM, TBM 250 °C and TBM 280 °C, and CBM 350 °C and CBM 380 °C and bamboo/coal blends from different torrefaction and carbonization temperatures. The derivative thermogravimetric curve (DTG) generated information including weight loss, temperature and changes in reaction time for the raw fuels and blends. The weight loss per temperature or an average of the fuel reactivity was determined from the expression provided in Eq. (1). On the DTG burning profiles, and from Tables 3–8 are the following features and data provided, the "volatile matter ignition temperature" (IT_{VM}) and the "ignition temperature fixed carbon" (IT_{FC}). The (IT_{VM}) is a point where the curve rises above zero line after the negative deflection observed due to moisture loss. The weight loss from the release of volatile matter begun from this point. Also, with an increase temperature and further weight loss, a point reached where the slope suddenly increases prior to the maximum peak height, is known as the “fixed carbon ignition temperature” (IT_{FC}) [14]. The corresponding data, in regards to time (min), temperature (°C), 1st derivative data (%/min) and weight loss (%) at the point where the (IT_{VM}), (IT_{FC}), along with the peak temperature occurs are obtained from the raw data generated by the TGA analyzer.

$$R_m = 100 \quad X \quad DTG_{\max} PT^{-1} \tag{1}$$

where R_m is the fuel reactivity (%/min/K), $DTG_{\max}$ is the weight loss rate (%/min), and PT is the peak temperature (K).

2.3. Material characteristics, energy and mass yield

The proximate analyses for all samples were conducted in accordance with the ASTM D-5142, with approximately 1 g used in determining the inherent moisture, ash content and volatile matter present and fixed carbon calculated by difference. The particle size of the samples was measured using a laser based particle size analyzer, namely a Mastersizer (2000) of Malvern Instruments Ltd. The calorific value known as the measure of the heat content was determined for both coal and bamboos using a Leco AC500 calorimeter in accordance with ASTM D5865-04. The system uses an electronic thermometer with an accuracy of 0.0001 °C to measure the temperature every 6 s, with the results obtained within 4.5–7.5 min. Ultimate and sulphur analyses of all samples were performed according to ASTM D 5373-02 and ASTM D 4239-05 for CHN and sulphur content, respectively using LECO CHN 628 with add on 628 S module.

The influence of thermal treatment on the mass and energy yield of the bamboo after torrefaction and low-carbonization at different temperature was evaluated using the mass yield and energy yield formula as stated in Eqs. (2) and (3). In addition, the calorific values for all samples were determined three times to ascertain the repeatability of the equipment. The mean values were used as the reported calorific values.

The mass yield (η_M) and energy yield (η_E) of the thermally treated bamboo were calculated using the equations reported by Park and Jang; Park et al. [4,8]. The mass yield η_M is obtained from the ratio of sample’s mass left after torrefaction and carbonization (M_t), and sample’s mass before torrefaction and carbonization (M_O) using Eq. (2);

$$\eta_M = \left(\frac{M_t}{M_o}\right) \text{dry basis} \tag{2}$$

The gross calorific value for untreated or raw bamboo is GCV_u, and GCV_t is the gross calorific value of torrefied or low-carbonized bamboo, and η_E is the energy yield obtained at different temperatures as stated below:

$$\eta_E = \eta_M \left(\frac{GCV_t}{GCV_u}\right) \text{dry basis} \tag{3}$$

3. Result and discussion

3.1. Physico-chemical properties of the coal and bamboo samples

The results of the proximate analysis conducted on the raw BM, TBM 250 °C and TBM 280 °C, and CBM 350 °C and CBM 380 °C bamboos are listed in Table 1 according to the location of the sample in the culms. The table shows the percentage moisture content in the raw BM leaves, culms and roots. These ranged from 5.83% to 13.53%, with the sample located at the bottom of the culm possessing the highest moisture content. High ash content of 9.25% was noted in the leaves of the raw bamboo, and 11.57% in the leaves of the 350 °C low-carbonized sample. The blend of all parts of the raw bamboo shows an ash content of 1.09%. A lower ash content could be found if the leaves were not added to the blend. Compared with other non-woody and woody biomasses such as Bermuda grasses and corn straws, oil palm and polar wood [15–17] the ash content for the raw BM was found to be much lower. The volatile matter in the total blend raw BM sample decreases from 97.2% to 49.05% after being carbonized at 380 °C, with a parallel relationship found existing between the volatile matter content in the total blend raw BM and the products torrefied from 250 °C to 380 °C. The fixed carbon content of the raw BM increases considerably from 1.71% to 45.51% with a decrease in the volatile and moisture content as the thermal treatment temperature intensified. This is due to the decomposition in the hydroxyl group within the bamboo.

3.2. Energy characteristics of the coal and bamboo samples

The results of the analyses for the raw BM, torrefied and low-carbonized samples are listed in Table 2. The loss in elemental oxygen and hydrogen content of the raw BM was more pronounced at carbonization temperature of 380 °C. Moreover, raw BM shows an upgrade in its carbon content from 46.70% to 60.35% after torrefacation at 280 °C. The carbon value obtained was higher compared to the carbon content obtained from other woody biomass torrefied between 280 °C and 300 °C, and held for 1 h by [18–21]. The effect of torrefication and low-carbonization on the energy content of BM can also be seen in Table 2. An increase in pre-treatment temperature to 380 °C lead to an increase in the calorific value of the raw BM from 17.57 MJ/kg to 28.02 MJ/kg, almost equal to the energy content of coal A but with a higher carbon content of 73.25% than coal A. It was also observed that the percentage nitrogen and sulphur content increases are minimal as the pre-treatment temperature increases. The firing of this biomass is expected to generate low NOx emission compared to coal A with the low nitrogen content of 1.85%.

In Table 2, it will be noted that energy yields were found to be greater than mass yields at increasing temperature for all samples. Energy yield was found to be higher for torrefied products compared to low carbonized bamboo samples. The changes in energy yield might be as a result of increase in thermal treatment temperature, which resulted into a decreased volatile matter, increased fixed carbon content and heat content of the raw BM. As was observed for all torrefied and carbonized products, energy yield was found to be greater than mass yield and more pronounced as pre-treatment temperature equal and above 280 °C.

The reactivities of the BM raw, TBM 250 °C and TBM 280 °C, and CBM 350 °C and CBM 380 °C bamboo samples, along with coal A are all depicted in Table 2. Raw BM has the highest fuel reactivity, and is expected to ignite at the lowest temperature compared to torrefied and carbonized bamboos due to its large amount of volatile matter. The fuel reactivity was found to decrease as the thermal heating temperature increases along with a decrease in volatile matter. It can be concluded that as the volatile matter increases, biomass fuel reactivity is expected to be much faster with ignition temperature reached at the lowest temperature. This is comparable to coal A (volatile matter of 45.08%).

3.3. The effect of thermal treatment on bamboo characteristics

The emission of water molecules through thermal heating resulted in the destruction of the hydroxyl group of the torrefied and low-carbonized bamboo, and the formation of bamboo products with different non-polar residue composition. The three different species of raw bamboos presented in Fig. 1 are seen within the zone at the top right corner of the energy diagram due to their high ratio of atomic O/C and H/C content and lower energy density. As the thermal treatment temperature increases to 250 °C, the energy density of both *Bambusa balcooa* and *Phyllostachys aurea* at 250 °C appears similar. As the temperature increases further

Table 2
Analysis data on coal A, raw, torrefied and carbonized *Bambusa multiplex*.

Samples	Cv (MJ/kg)	R_m (%/min/K)	η_m (%)	η_e (%)	VM db (%)	C (%)	H (%)	O (%)	N (%)	S (%)
BM raw	17.57	13.28			97.20	46.70	6.47	59.98	0.21	UT
TBM 250 °C	18.30	12.30	60.80	63.31	89.56	46.22	6.06	60.15	0.32	0.005
TBM 280 °C	22.97	10.62	46.30	60.53	68.05	60.35	5.48	45.51	0.38	0.006
CBM 350 °C	27.81	10.34	33.00	52.70	54.46	71.28	4.70	33.92	0.51	0.009
CBM 380 °C	28.02	10.35	29.3	46.72	49.05	73.25	4.33	31.59	0.51	0.032
Coal A	28.07	9.90			45.08	71.65	4.94	35.15	1.85	0.276

Db: on dry basis; VM: volatile matter; Cv: calorific values; R_m: fuel reactivity and UT: untraceable.

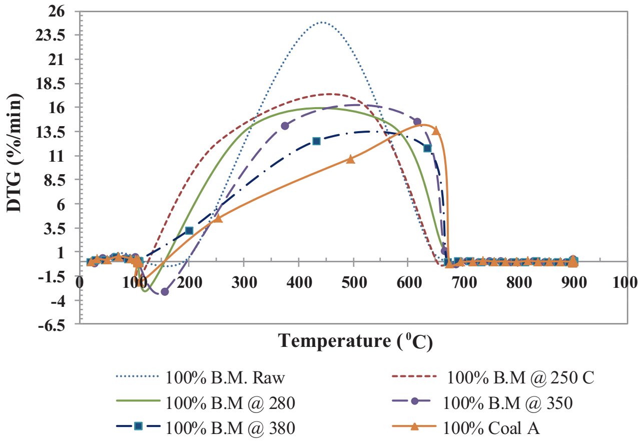

Fig. 2. DTG curves for Coal A, raw, torrefied and low-carbonized bamboo.

to 280 °C, both *Bambusa balcooa* and *Bambusa multiplex* samples increase further in the energy density, and move towards that of coal A. This was as a result of intense devolatilization and decarboxylation of the bamboo samples. A wide range in the sample characteristics can be seen in the plot as the biomass samples decomposed further from 280 °C to 350 °C, with their H/C and O/C ratios moving towards that of coal A. Further increase in low carbonization temperatures to 350 °C and 380 °C for *Bambusa balcooa and Bambusa multiplex*, respectively, produced solid fuels with similar characteristics in terms of energy density with coal A. The data obtained are supported by the calorific values depicted in Table 2. In summary, the results show a clear trend, namely, increasing temperatures lead to an increase in energy density in the bamboo materials as indicated by the direction of the arrow in Fig. 1.

3.4. Combustion profile of coal A, raw and thermal treated Bambusa multiplex samples

The thermogravimetric analysis (TGA) technique utilized in this investigation provided an insight into the reactivity and combustibility of each sample of BM bamboo and its co-fired potential with coal. The DTG profiles for coal A, raw BM, TMB 250 °C, TMB 280 °C, CBM 350 °C and CBM 380 °C fuels are depicted in Fig. 2. The figure shows distinctly different reaction regions in the profiles. The first region (0–100) °C occurs due to the evaporation of the moisture at low boiling points within the fuels. The second and third reaction stages for the raw BB (106–443 °C and 443–642 °C) occur as a result of volatile removal and oxidation of the remaining char respectively. The two main reactions that occur during the thermogravimetric analysis of biomass and coal are the decomposition of the volatile matter contents and chars in both fuels. It was observed from Fig. 2 that all the bamboo samples followed different burning profiles as a result of the modification made to the bamboo through thermal treatment. These profiles indicate that the raw BB may devolatilize and burnout before coal A char ignites, whereas CBM 380 °C sample paralleled coal A rate of slow devolatilization and ignition, and reaches peak temperature slightly before coal A. This implies a close parallel in reactivity, devolatilization and burnout. As noted in Table 3, the raw BM has the highest volatile matter content of 97.20%, and the lowest ignition temperature, with maximum combustion reached at the peak temperature of 442.61 °C. Moreover, as the thermal pre-treatment temperature increases from the lower torrefied temperature to the higher low-carbonized temperature, the ignition temperatures also increase. This would appear to be due to the increase in carbon content and reduction in volatile content of the fuels. In conclusion, it can be seen below that the raw BM is the easiest of the bamboo samples to ignite whilst coal A is likely to be the most difficult as it ignites at the highest temperature and has the lowest volatile content in relative terms.

3.5. DTG profile for blends of raw BM and Coal A at different weight ratio

Comparison was made on the combustion characteristic and effect of replacing the raw BM with coal at different weight proportion (%). The co-combustion DTG profiles of raw BM and Coal A blends with 90%BM + 10% Coal A, 70%BM + 30% Coal A, 50% BM + 50% Coal A and 25% BM + 75% Coal A are depicted in Fig. 3. The burning profiles of the fuels were obtained using a TGA analyzer and with this, the ignition, burning and peak temperature were obtained for each of the fuel ratios (see Table 4). The blend with the lowest coal proportion (10%) had a burning profile similar to that of raw BM, i.e. with the highest peak temperature profile and reactivity compared to the raw BM. As the coal proportion increases in the blend, reactivity decreases and ignition, peak and burnout temperatures increase. In Table 4, it will be noted that the raw BM char has an initial ignition temperature of 202.75 °C compared to 237.02 °C obtained from 25% BM + 75% Coal A sample. This increase in ignition temperature is attributed to the decrease in volatile matter and increase in carbon

Table 3
Ignition, peak and burnout temperature for Coal A, raw BM and thermal-treated BM.

Sample	IT (V_m) (°C)	IT (FC) (°C)	Peak temp (°C)	Burnout temp (°C)	Weight loss (%)	FC db (%)	Ash db (%)	VM db (%)
Raw BM	106.98	202.75	442.61	641.60	99.19	1.71	0.79	97.20
TBM 250 °C	108.65	252.78	508.50	697.16	95.94	7.04	4.97	89.56
TBM 280 °C	125.90	312.49	568.96	702.23	94.14	27.62	4.55	68.05
CBM 350 °C	156.02	375.38	615.99	707.51	94.92	41.53	4.70	54.46
CBM 380 °C	199.52	432.23	635.04	712.30	94.14	45.51	5.85	49.05
100% Coal A	254.38	494.69	651.24	737.79	90.55	46.66	8.26	45.08

IT: ignition temperature; FC: fixed carbon; Db: on dry basis; IT (V_m): ignition of volatiles and IT (FC): ignition of FC.

Table 4
Ignition, peak and burnout temperature for raw BM, Coal A, and BM/Coal A blend at different Coal A wt% ratio.

Sample	IT (V_m) (°C)	IT (FC) (°C)	Peak temp (°C)	Burnout temp (°C)	Weight loss (%)	Ash db (%)
Raw BM	106.85	202.75	442.61	672.23	99.19	0.79
Raw BM +10% Coal A	106.9	212.47	455.87	692.85	98.05	1.97
Raw BM +30% Coal A	107.03	222.55	469.77	693.41	96.44	3.71
Raw BM +50% Coal A	107.12	230.11	482.98	694.95	94.74	5.49
Raw BM +75% Coal A	107.56	237.02	495.71	696.09	92.81	7.36
100% Coal A	254.38	494.69	651.24	717.58	90.55	8.26

IT: ignition temperature; FC: fixed carbon; VM: volatile matter and Db: on dry basis.

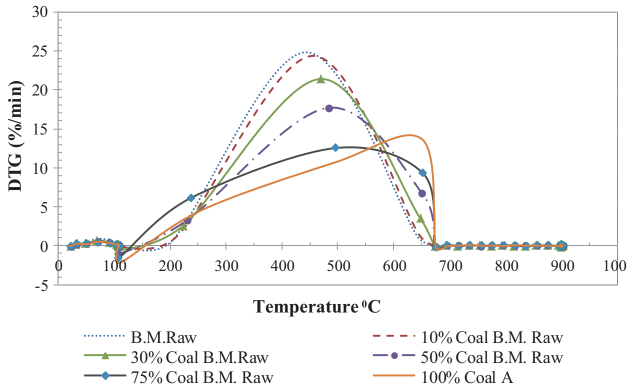

Fig. 3. DTG curves for raw BM, Coal A and BM/Coal A at different wt% ratios.

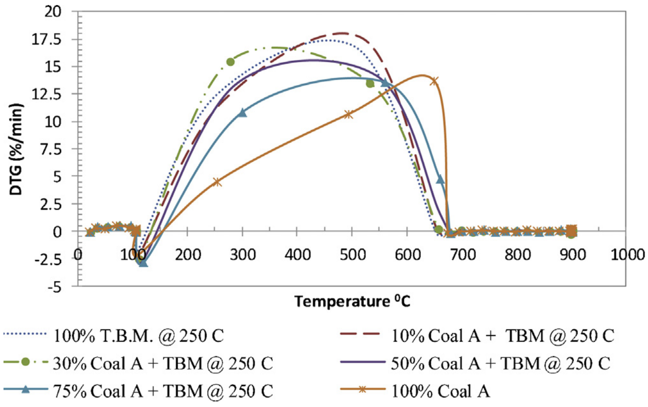

Fig. 4. DTG curves for TBM 250 °C, Coal A and BM/Coal A at different wt%.

content of the blend due to an increase coal proportion. Raw BM has the lowest peak temperature and highest weight loss of 99.19%, which can be attributed to the loss of its exceptionally high volatile content. Of all the blending ratios tested, the 10% coal A and 90% BM achieved the maximum combustion at the lowest peak temperature, while with the blending ratio of 75% coal + 25% BM, the ignition and peak temperature provided the highest peak temperature, but is slightly lower than coal A. The conclusion from these results are that if biomass is combusted alone, ignition will be rapid and burnout would be completed at low temperatures. If raw BM is blended with coal A, it should be added not more than 50% in order to combust compatibly with coal A. A higher proportion of raw BM than this, will result in early burnout of BM before the coal ignites.

3.6. DTG profile for blends of TBM (250 °C and 280 °C) and Coal A at different wt% ratios

The co-combustion attributes of TBM 250 °C and 280 °C are shown in Figs. 4 and 5, respectively. The DTG profiles for TBM 250 °C and 90% TBM 250 °C + 10% Coal A are similar but coal A exhibits a burning profile entirely different from the rest of the fuels utilized. The fixed carbon within Coal A ignited at temperature of 494.70 °C in comparison with TMB 250 °C and TBM 280 °C at 252.78 °C and 312.49 °C, respectively. Among all the fuels illustrated in Fig. 4 and listed in Table 5, the 100% bamboo sample (BM 250 °C) was found to be the most reactive and the easiest to ignite. Ignition temperature increased as the coal ratio within the blend increased. Ignition temperature of the torrefied fuel also increased as the temperature increased from 250 °C to 280 °C shown in Tables 5 and 6. This is reflected in an increase in the fixed carbon from 1.7% raw to 7.04% in TBM 250 °C and to 27.62% in TBM280 °C sample with a parallel reduction in volatile matter content. This further indicates changes

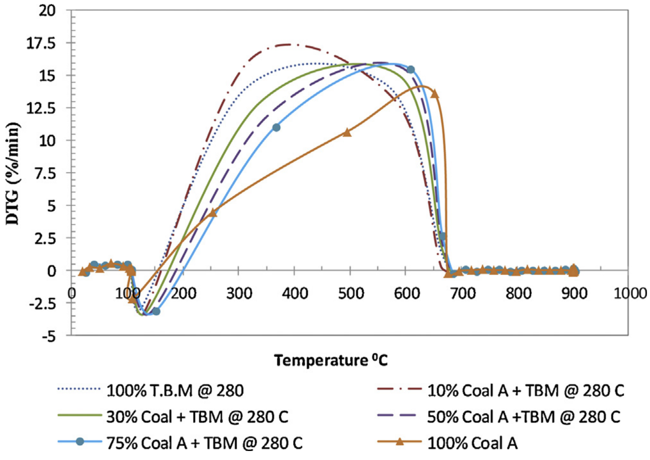

Fig. 5. DTG curves for TBM 280 °C, Coal A and BM/Coal A at different wt%.

Table 5
Ignition, peak and burnout temperature for Coal A, TBM 250 °C, and TBM 250 °C with different proportions of coal A.

Sample	IT (V_m) (°C)	IT (FC) (°C)	Peak temp (°C)	Burnout temp (°C)	Weight loss (%)	Ash db (%)
TBM 250 °C	106.98	252.78	508.50	676.68	95.50	4.97
TBM 250 °C +10% Coal A	110.46	265.33	521.14	677.8	95.42	3.99
TBM 250 °C + 30% Coal A	113.16	277.43	533.46	678.79	93.75	6.60
TBM 250 °C + 50% Coal A	118.21	288.97	545.39	679.74	92.96	7.39
TBM 250 °C +75% Coal A	121.00	300.55	560.57	680.49	92.35	6.98
100% Coal A	254.38	494.70	651.24	696.59	90.55	8.26

IT: ignition temperature; FC: fixed carbon; VM: volatile matter and Db: on dry basis.

Table 6
Ignition, peak and burnout temperature for Coal A, TBM 280 °C, and TBM 280 °C with different proportions of coal A.

Sample	IT (V_m) (°C)	IT (FC) (°C)	Peak temp (°C)	Burnout temp (°C)	Weight loss (%)	Ash db (%)
TBM 280 °C	125.90	312.49	568.96	702.23	94.33	4.55
TBM 280 °C + 10% Coal A	131.57	324.63	579.99	703.25	94.08	4.53
TBM 280 °C + 30% Coal A	135.62	336.77	589.98	704.42	93.45	7.05
TBM 280 °C + 50% Coal A	144.31	348.92	599.43	705.31	92.49	8.06
TBM 280 °C + 75% Coal A	151.39	366.81	608.23	706.33	91.83	7.92
100% Coal A	254.38	494.69	651.24	696.59	90.55	8.26

IT: ignition temperature; FC: fixed carbon; VM: volatile matter and Db: on dry basis.

Table 7
Ignition, peak and burnout temperature for Coal A, CBM 350 °C, and CBM 350 °C with different proportions of coal A.

Sample	IT (V_m) (°C)	IT (FC) (°C)	Peak temp (°C)	Burnout temp (°C)	Weight loss (%)	Ash db (%)
CBM 350 °C	156.00	375.375	615.993	707.515	95.1308	4.70
CBM 350 °C + 10% Coal A	165.04	388.621	622.867	708.634	93.6073	5.37
CBM 350 °C + 30% Coal A	173.02	406.223	628.934	709.667	93.2396	4.84
CBM 350 °C + 50% Coal A	181.57	415.719	634.145	710.753	92.1842	5.44
CBM 350 °C + 75% Coal A	192.50	418.361	629.681	711.548	92.1777	8.10
100% Coal A	254.38	494.691	651.237	696.585	90.5456	8.26

IT: ignition temperature; FC: fixed carbon; VM: volatile matter and Db: on dry basis.

Table 8
Ignition, peak and burnout temperature for Coal A, CBM 380 °C, and CBM 380 °C with different proportions of coal A.

Sample	IT (V_m) (°C)	IT (FC) (°C)	Peak temp (°C)	Burnout temp (°C)	Weight loss (%)	Ash db (%)
CBM 380 °C	199.52	432.23	635.04	712.30	94.143	5.85
CBM 380 °C + 10% Coal A	211.31	447.855	640.282	713.362	93.2916	6.92
CBM 380 °C + 30% Coal A	222.52	456.156	642.747	714.464	92.8438	7.42
CBM 380 °C + 50% Coal A	232.82	469.238	645.851	715.489	91.8379	8.27
CBM 380 °C + 75% Coal A	243.62	481.978	648.636	716.496	90.9325	8.63
100% Coal A	254.38	494.691	651.237	696.585	90.5456	8.26

IT: ignition temperature; FC: fixed carbon; VM: volatile matter and Db: on dry basis.

in the molecular structure of the bamboo samples. For the TBM 250 °C sample and different coal weight ratio fuels, it is evident that all fuels utilized are more reactive than coal A based on the ignition temperature, corresponding DTGmax and weight loss attained during the oxidation stage. The same trend may be observed in TBM 280 °C with co-fired coal A blends as the torrefied temperature and the coal blend ratio increase (Table 6). The bamboo sample is noted to have almost the same ash content as coal A.

3.7. Effect of low-carbonization temperatures (350 °C and 380 °C) and coal blending on co-combustion characteristic of bamboo and coal

The energy and mass yield of the CBM 350 °C and CBM 380 °C samples utilized in the co-combustion investigation were found to be higher than that obtained during torrefaction of the sames sample (Table 6). These results are supported by the investigation conducted by Park and Jang [4] on torrefied and carbonized biomass, where the author found a higher energy yield of 98% at 275 °C compared to 45% energy yield attained at the low carbonization temperature of 375 °C. The significant improvement made to the physicochemical properties of the CBM at 350 °C and CBM 380 °C might be as a result of the decomposition in cellulose and hemicelluloses constituent of the bamboo, with potential decomposition in the lignin at 380 °C. The devolatilization of the bamboo under these thermal temperatures resulted in an increase in the product's calorific value from 17.57 MJ/kg to 27.81 MJ/kg at CBM 350 °C and 28.02 MJ/kg CBM 380 °C respectively, with higher fixed carbon and lower volatile matter content compared to the torrefied products.

Tables 7 and 8 show the thermal characteristics of samples CBM 350 °C, CBM 380 °C, and their coal blend at different weight percentage. As illustrated in these tables, ignition temperatures for the carbonized samples CBM 350 °C and CBM 380 °C were lower than that for the blended coal/CBM 350 °C and 380 °C products, and coal A. With an increase in weight percentage of coal mixed with carbonized bamboo, the DTG profiles for all blended products deviated from the raw bamboo and moves towards that of coal band, resulting in delays in fuel ignition. At 10%, 30%, 50% and 75% coal A/CBM 350 °C and CBM 380 °C, the ignition and peak temperatures were found to be lower than the ignition and peak temperature for coal A. With increasing coal proportion in the low carbonized products (CBM 350 °C and CBM 380 °C), a decrease in weight loss was noted as the percentage coal in the blend increases. In conclusion, it may be noted from Tables 7 and 8 that the CBM 350 °C, CBM 380 °C samples and almost all the fuel blends are more reactive than coal A.

4. Conclusions

The chemical analyses and DTG test curves provide detailed combustion and co-combustion characteristics of the raw, torrefied and low carbonized bamboo samples and the coal used in this research with their blends. The following conclusions have been drawn from that data:

1. The results attained from the proximate analysis of the raw BM shows that bamboo leaves have the highest ash content of 8.56% and fixed carbon of 4.14%, moisture content of 7.47% and volatile matter of 79.82%. A decrease in the ash content to 0.99% occurs where blending the leaves with the stem. It was observed that, as the pre-treatment temperature increased to 380 °C, the volatile matter in the blend of raw bamboo materials (stem, leaves and root) decreases from 97.2% in raw blend to 49.05% in final BB,

while fixed carbon increases considerably from 1.71% to 45.51% in the final carbonized product.

2. A decrease in energy yield (%) was observed, which occurs due to the increase in calorific value with increasing pre-treatment temperature from 250 °C to 380 °C. In addition, the TBM and CBM bamboo samples appear to move closer towards that of coal in the Van Krevelen diagram, i.e. in C/H versus C/O plot. The raw bamboo has the highest fuel reactivity, and was found to be more reactive at the lowest ignition and burnout temperatures compared to all fuels utilized.
3. In regard to the combustion characteristics, the DTG curve for the CBM 380 °C was closer to that attained by coal A than those shown by other fuels in different proportions and temperatures. The peak combustion temperature of the raw bamboo was found to be higher than the torrefied and carbonized bamboo samples. The same raw BM was also the easiest to ignite probably due to possessing the highest volatile matter content. The delay in ignition temperature (Vm) for the torrefied and low carbonized fuel compared to raw B.M is considered to be a result of lower volatile matter and molecular modification (increased carbon) in the hemicellulose structure of the TBM and CBM samples.
4. The blending of raw bamboo with coal A at different ratios by weight provided various ignition and peak temperatures all of which were found to be lower than that of coal A. Moreover, as the proportion of coal in the mix increases, the DTG profiles for all blended fuels were found to deviate progressively from raw bamboo through to the end point of coal A.
5. Both thermal processes are known to aid and improve combustion, and therefore important for applications. Based on the empirical data obtained from this investigation, carbonized bamboo will be more compatible as a co-fired or primary fuel that could be used in the existing pulverized power plant in South Africa.

In summary, this research has sought to establish the chemical properties and burning characteristics of various raw and thermally treated bamboo samples and coal/bamboo blends in various proportions. On the basis of combustibility, torrefied bamboo samples from this research have shown to ignite at relatively low temperatures and to be a highly reactive, which could serve as a fuel in a fluidized bed combustor. Carbonized bamboo, however, is considered to be a better fuel for existing pulverized boilers in South Africa as an alternative or co-fired with coal.

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